UNITED STATES PATENT APPLICATION

for

CHANNEL ALLOCATION IN BROADBAND ORTHOGONAL FREQUENCY-DIVISION MULTIPLE-ACCESS/SPACE-DIVISION MULTIPLE-ACCESS NETWORKS

Inventors:

Hui Liu

Hujun Yin

Li Xiaodong

Fuqi Mu

prepared by:

BLAKELY, SOKOLOFF, TAYLOR & ZAFMAN LLP

12400 Wilshire Boulevard

Los Angeles, CA 90025-1026

(408) 720-8598

File No.: 005158.P003

CHANNEL ALLOCATION IN BROADBAND ORTHOGONAL FREQUENCY-DIVISION MULTIPLE-ACCESS/SPACE-DIVISION MULTIPLE-ACCESS NETWORKS

5 ### FIELD OF THE INVENTION

The present invention relates to the field of communications systems; more particularly, the present invention relates to orthogonal frequency-division multiple-access (OFDMA) networks that employ space-division multiple-access.

10

BACKGROUND OF THE INVENTION

For broadband wireless networks that support mixed traffic, it is required that a medium access control (MAC) be able to effectively adapt to changing channel conditions and traffic requirements. One of the key

15 resources in wireless communication is the spatial diversity provided by antenna arrays. Efficient exploitation of spatial diversity is fundamentally important to resource critical wireless applications. See Tsoulos, "Smart Antennas For Mobile Communication Systems: Benefits and Challenges," Electronics and Communication Engineering Journal, Vol. 11(2), April 1999.

20 One of the most aggressive ways of exploiting the spatial diversity is space-division multiple-access (SDMA), or spatial multiplexing, that attempts to multiply the throughput of a wireless network by introducing

"spatial channels". The benefits of SDMA in narrowband applications have

be investigated by Shad et al., "Indoor SDMA Capacity Using a Smart

Antenna Base Station," IEEE Proc. ICUPC'97, pp. 868--872, 1997; Farsakh et

al., "On the Mobile Radio Capacity Increase Through SDMA," Accessing,

5   Transmission, Networking Proceedings, pp. 293-297, 1998; Xu et al.,

"Throughput Multiplication of Wireless LANs for Multimedia Services:

SDMA Protocol Design," Proc. Globecom'94, San Francisco, CA, November

1994; Ward et al., "High Throughput Slotted ALOHA Packet Radio

Networks with Adaptive Arrays," IEEE Trans. COM, Vol. 41(3), pp. 460-470,

10   March 1993. The narrowband SDMA scheme is particularly suitable for

fixed wireless networks where the spatial characteristics are relatively stable.

For a system with M antenna elements, the underlying idea is to allow M

subscribers to share a time-division multiple-access (TDMA) slot through M

spatial channels/slots, so that the total number of non-interfering traffic

15   channels can be increased by M fold.

Though intuitively promising, an obvious flaw of this scheme is that

spatial channels are rarely orthogonal in practice. In other words, traffic

over SDMA channels are mutually interfering. If multiple subscribers are

assigned to one time slot without considering these spatial characteristics,

the one with an unfavorable spatial configuration may experience significant

throughput disadvantages. Since the effectiveness of spatial separation

depends on the base-station array responses (often referred to as the spatial

signatures) of all co-slot subscribers and the spatial processing technique

5   employed, the instantaneous signal-to-noise-plus-interference ratio (SINR)

of spatially multiplexed outputs can vary dramatically. This problem is

investigated by Ward et al., "High Throughput Slotted ALOHA Packet

Radio Networks with Adaptive Arrays," IEEE Trans. COM, Vol. 41(3), pp

460-470, March 1993, where collision due to un-resolvable packets (when the

10   arrival angles of multiple packets are within a threshold) is accounted for.

Although the analysis is somewhat simplified, the study reveals some of the

key limitations of basic SDMA scheme.

A fundamental solution to the above problem is the "channel-aware"

MAC protocol that assigns traffic channels based on the spatial

15   characteristics of the subscribers. Using such a protocol, the performance of

SDMA system can be enhanced with spatial signature-based scheduling

(e.g., assigning the "less-interfering" subscribers to the same time slot to

increase the traffic throughput). The MAC treatment allows a system to

exploit the spatial diversity in an efficient manner using spatial processing

with fixed-complexity. Several scheduling algorithms are proposed and

studied for "narrow band" systems where the spatial characteristics can be

described by a one-dimensional vector; see Shad et al., "Indoor SDMA

Capacity Using a Smart Antenna Base Station," IEEE Proc. ICUPC'97, pp.

5   868-872, 1997; Farsakh et al., "On the Mobile Radio Capacity Increase

through SDMA," Accessing, Transmission, Networking Proceedings, pp.

293-297, 1998; and U.S. Patent No. 6,041,237, "Method of Channel

Allocation," issued March 21, 2000.

All of the existing channel allocation schemes, however, consider

10   "narrowband" TDMA wireless network in conjunction with SDMA. None

of them is applicable to broadband wireless networks. The prime reason is

that in broadband application, subscribers' spatial channels are two-

dimensional, in both space and frequency, and channel assignment under

spatial multiplexing becomes a more involved problem.

15   Recently, there is an increasing interest in frequency division multiple

access (OFDMA) based broadband wireless networks. OFDMA can be

viewed from one perspective as attempting to achieve system capacity over

multiple-subscriber broadband wireless channels.

SUMMARY OF THE INVENTION

A network is described. In one embodiment, the network comprises

multiple subscriber units to communicate with the base station using an

orthogonal frequency-division multiple-access (OFDMA) protocol, and a

5   base station. The base-station includes a memory unit to store broadband

spatial signature vectors associated with each subscriber and traffic channel

allocation logic. The vectors are a function of frequency. The traffic channel

allocation logic allocates OFDMA channels using the broadband spatial

signature vectors of the subscribers.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be understood more fully from the detailed description given below and from the accompanying drawings of various embodiments of the invention, which, however, should not be taken

5   to limit the invention to the specific embodiments, but are for explanation and understanding only.

Figure 1A illustrates multiple subscribers.

10   **Figure 1B** illustrates randomly assigning subscribers to channels and the idea of "spatial signature-aware" channel assignment, where less interfering subscribers are assigned to the same traffic slot to increase system capacity.

15   **Figure 2** shows accommodating a high data rate with parallel narrowband data streams transmitted over OFDMA traffic channels.

Figure 3 illustrates channel assignment in OFDMA/SDMA in the presence of on-going traffics.

20

Figure 4 shows the achievable rates of accessing subscribers in each of the OFDMA traffic channels in the presence of on-going subscribers.

Figure 5 is a block diagram of one embodiment of an OFDMA/SDMA base-station.

Figure 6 is a decision making flow of one embodiment of the

5   OFDMA/SDMA traffic channel allocation logic.

DETAILED DESCRIPTION OF THE PRESENT INVENTION

A network described herein combines orthogonal frequency-division multiple-access (OFDMA) with space-division multiple-access (SDMA) to provide an OFDMA/SDMA protocol that offers an increase in capacity,

5   while assigning OFDMA/SDMA traffic channels to multiple-access subscribers based on their broadband (two-dimensional) channel characteristics. In one embodiment, such a network is a cellular network implementing OFDMA in conjunction with spatial multiplexing in a broadband wireless cellular network. The cellular network includes a base-

10   station with spatially separated transceivers and multiple subscribers communicating with the base-station using an OFDMA protocol. The term "subscriber" or "subscribers" is used herein to refer to a subscriber unit or device.

The network includes traffic channel allocation logic that increases,

15   and potentially maximizes, the network throughput based on the broadband propagation characteristics between the base-station and the subscribers. In one embodiment, each traffic channel is a cluster of OFDM sub-carriers that may be shared by multiple subscribers through spatial multiplexing. When a new link between the base-station and a subscriber is to be established, the

traffic channel allocation logic first estimates two-dimensional (space and frequency/time) broadband propagation channels between the base-station and the new subscriber. Frequency and time are the same time represented in two different domains. The traffic channel allocation logic then

5   accommodates a rate request received from the new subscriber by assigning traffic channels that utilizes a predetermined (e.g., the minimum) amount of transmission power (in comparison to the amount of transmission power necessary to transmit over one or more other OFDMA traffic channels that were not assigned to the new subscriber) and causes a certain amount of

10   interference (e.g., the least interference in comparison to the interference to other subscribers caused by the new subscriber using one or more of the OFDMA traffic channels that were not assigned to the new subscriber) to co-channel subscribers. The rate request is received from the subscriber either prior to the process of establishing the new link or concurrently therewith.

15   In alternative embodiments, the traffic channel allocator logic assigns traffic channels that require use of an amount of transmission power greater than the minimum and/or cause an amount of interference greater than those channels that cause the least interference (if used for the new subscriber's traffic). Such assignments may, for example, be used on other

channel allocation or loading requests by made at the same time or scheduled to occur in the future.

In the following description, numerous details are set forth in order to provide a thorough understanding of the present invention. It will be

5   apparent, however, to one skilled in the art, that the present invention may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form, rather than in detail, in order to avoid obscuring the present invention.

Some portions of the detailed descriptions which follow are presented

10   in terms of algorithms and symbolic representations of operations on data bits within a computer memory. These algorithmic descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-

15   consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. It has proven convenient at times, principally for

reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like.

It should be borne in mind, however, that all of these and similar terms are to be associated with the appropriate physical quantities and are

5   merely convenient labels applied to these quantities. Unless specifically stated otherwise as apparent from the following discussion, it is appreciated that throughout the description, discussions utilizing terms such as "processing" or "computing" or "calculating" or "determining" or "displaying" or the like, refer to the action and processes of a computer

10   system, or similar electronic computing device, that manipulates and transforms data represented as physical (electronic) quantities within the computer system's registers and memories into other data similarly represented as physical quantities within the computer system memories or registers or other such information storage, transmission or display devices.

15   The present invention also relates to apparatus for performing the operations herein. This apparatus may be specially constructed for the required purposes, or it may comprise a general purpose computer selectively activated or reconfigured by a computer program stored in the computer. Such a computer program may be stored in a computer readable

storage medium, such as, but is not limited to, any type of disk including

floppy disks, optical disks, CD-ROMs, and magnetic-optical disks, read-only

memories (ROMs), random access memories (RAMs), EPROMs, EEPROMs,

magnetic or optical cards, or any type of media suitable for storing electronic

5   instructions, and each coupled to a computer system bus.

The algorithms and displays presented herein are not inherently

related to any particular computer or other apparatus. Various general

purpose systems may be used with programs in accordance with the

teachings herein, or it may prove convenient to construct more specialized

10   apparatus to perform the required method steps. The required structure for

a variety of these systems will appear from the description below. In

addition, the present invention is not described with reference to any

particular programming language. It will be appreciated that a variety of

programming languages may be used to implement the teachings of the

15   invention as described herein.

A machine-readable medium includes any mechanism for storing or

transmitting information in a form readable by a machine (e.g., a computer).

For example, a machine-readable medium includes read only memory

("ROM"); random access memory ("RAM"); magnetic disk storage media;

optical storage media; flash memory devices; electrical, optical, acoustical or

other form of propagated signals (e.g., carrier waves, infrared signals, digital

signals, etc.); etc.

5   Overview

Efficient exploitation of spatial diversity in high-speed wireless

network is a challenging task due to the broadband nature of spatial channel

characteristics. In OFDMA networks, the wide spectrum is partitioned into

parallel narrowband traffic channels. The methodology described herein

10   increases, and potentially maximizes, the capacity of a broadband

OFDMA/SDMA network through intelligent traffic channel assignment.

The concept of channel assignment for narrowband SDMA networks

is illustrated in Figure 1. In such application, each spatial channel can be

described by a vector, referred to herein as a narrowband "spatial

15   signature." For a system with M antenna elements, the spatial signature can

be represented as $A\_i\, a\_i$, where A_i is a fading coefficient of the channel

and $a\_i=[a\_1i, a\_2i, ..., a\_Mi]$ is an Mx1 vector that characterizes the relative

complex gains between antennas. The level of interference between co-

channel subscribers (sharing the same spectral resource, e.g., the same time

slot/the same frequency/the same code (e.g., the spreading code) is

determined by the degree of orthogonality between their corresponding

spatial signatures. (See Farsakh et al., "On the Mobile Radio Capacity

Increase Through SDMA", Accessing, Transmission, Networking

5   Proceedings, pp. 293-297, 1998.) Referring to the example in Figure 1A, the

spatial signatures of subscribers 1, 3, and 5 are almost orthogonal, so are

those of subscribers 2 and 4. On the other hand, the spatial signatures of

subscribers 1 and 2 are near aligned, indicating strong mutual interference

should they be assigned to the same traffic channel.

10   Conventional SDMA simply assigns subscribers to their traffic

channels (time slots in this case) in a pre-determined order. For example, in

top of Figure 1B, subscriber 1 and 2 are allocated to the same time slots,

while being separated in space. Similarly, subscribers 3 and 4 are allocated

to the same time slot while being separated in space. The possibility of

15   strong interference between co-channel subscribers (in this particular

example: slot 1, between subscribers 1 and 2; slot 2, between subscribers 3

and 4) is high. To reduce the interference level and improve the system

capacity, traffic channels are assigned in a way that the most (if not all)

interfering subscribers are allocated to different time slots (as in bottom of

Figure 1B). By lifting the worst case performance, significant capacity gains can be achieved using this strategy without undue complexity in spatial processing.

The channel assignment problem becomes much more involved in

5   broadband applications (e.g., broadband antenna array systems, etc.) where the spatial signature is no longer a vector. In the case of the OFDMA-based network described herein, high data rate traffic is accommodated with multiple low-rate (narrowband) data streams over orthogonal narrowband traffic channels. These narrowband traffic channels, centered at different

10   frequencies, provide a parallel structure for higher flexibility and ease of implementation. Figure 2 illustrates such a structure in which high data rate traffic 201 is provided in the form of parallel data streams over orthogonal narrowband traffic channels centered at different frequencies. As a result, the "broadband spatial signature" associated with each subscriber becomes a

15   two-dimensional matrix, or a set of narrowband spatial signature vectors that are a function of the frequency. In one embodiment, the spatial signature of subscriber i in OFDMA is given by

$$[A\_i1 \, a\_i1, \quad A\_i2 \, a\_i2, \, ..., \quad A\_iK \, a\_iK],$$

where A_ik is the fading coefficient of traffic channel k, a_ik is the Mx1 spatial signature vector of traffic channel k, and K is the total number of OFDMA traffic channels (in frequency). When K=1, the above reduces to a narrowband setup. In contrast to the narrowband case where the spatial signature is "invariant" to the channel assignment, a broadband subscriber experiences different fading and spatial characteristics in different traffic channels.

A goal of broadband traffic channel assignment in OFDMA described herein is to allocate traffic channels to new subscribers (in the presence of on-going traffics) in a way that increases, and potentially maximizes, the system capacity. The process may be illustrated using Figure 3. Referring to Figure 3, on-going traffic identified by solid blocks occupy certain numbers of OFDMA traffic channels (e.g., channels 1, 2, 3, and 6), some of which, e.g., traffic channel 1, are shared by more than one subscribers using spatial multiplexing. The unshaded blocks represent OFDMA channels that are unoccupied (i.e., not being used). The shaded block represents traffic that is to be allocated or assigned to one or more OFDMA channels.

In one embodiment, several factors may be considered in determining

which set of traffic channels are to be assigned to a new subscriber: (a) the

channel fading conditions of the new subscriber at all traffic channels, (b) the

spatial signature vectors of the new subscriber across all traffic channels, (c)

5   the spatial signature vectors of on-going traffic, and (d) the data rate of on-

going traffic of subscribers that have already been in communication with

the base-station.

In the communication system described herein, channel allocation

logic performs "channel-aware" traffic channel allocation. In one

10   embodiment, the channel allocation logic provides bandwidth on demand

and efficient use of spectral resources (e.g., OFDMA traffic channels) and

spatial resources (e.g., the physical location of subscribers as it pertains to

spatial beamforming) and performs traffic channel assignment based on

broadband spatial channel characteristics of a requesting subscriber and on-

15   going subscribers. Thus, the channel allocation may reduce resource usage

(e.g., reduce usage of OFDMA channels).

In responding to a link request from a new subscriber, or when the

base-station has data to transmit to a standby subscriber, the logic first

estimates the spatial signature of the corresponding subscriber over all, or a

predetermined portion of OFDMA traffic channels. In one embodiment, the

estimated information, along with the spatial characteristics of on-going

subscribers are used to determine the achievable rate of the accessing

subscriber over each of the OFDMA channels (with the presence of on-going

5   SDMA subscribers). In an alternative embodiment, the estimated

information and the spatial characteristics associated with on-going traffic

channels are used to determine the SINR of the accessing subscriber over

each of the OFDMA channels. The spatial characteristics may be stored in a

register or other type of storage location (e.g., a spatial signature register).

10   In one embodiment, traffic channels that have the highest achievable rates

and will not affect the rates of on-going traffic are assigned to the accessing

subscriber to satisfy the rate request of the accessing subscriber.

In an alternative embodiment, traffic channels without the highest

achievable rates may be allocated to a new subscriber, while leaving the

15   traffic channels with the highest achievable rates to be allocated in the

future. Similarly, traffic channels that affect the rates of subscribers due to

some level of interference with on-going traffic may be allocated in certain

instances. For example, in one embodiment, such allocations may occur

because the achievable rate is so high that the degradation of on-going traffic is tolerable.

A base-station architecture that communicates with multiple subscribers in an OFDMA/SDMA fashion is also disclosed. In one

5   embodiment, the base-station includes multiple receiving antennas, each of which is connected to a down-converter, an OFDM demodulator, a 2-D spatial signature estimator, an on-going traffic register and an on-going traffic spatial signature register, an OFDMA/SDMA traffic channel allocation logic, an OFDMA medium access controller, an OFDM modem, an

10   OFDM broadband beamformer, multiple up-converters, and multiple transmission antennas, each connected to one of the upconverters.

Figure 5 is a block diagram of an antenna array base-station that communicates with multiple subscribers through OFDMA and spatial multiplexing. Referring to Figure 5, the base-station 500 comprises receiving

15   antenna array 500, a set of down-converters 501 coupled to receiving antenna array 300, an OFDM demodulator 502, a broadband (2-D) spatial signature estimator 503, an on-going traffic register 504, an OFDMA/SDMA traffic channel allocation logic 505, an on-going traffic spatial signature register 506, an OFDMA medium access controller (MAC) 507, an OFDM

modem 510, a set of parallel narrowband beamformers 509, a set of up-converters 508 and a transmission antenna array 511.

Uplink signals, including the accessing signal from a requesting subscriber, are received by receiving antenna array 500 and down-converted

5   to the base-band by down-converters 501. The base-band signal is demodulated by OFDM demodulator 502 and also processed by the 2-D spatial signature estimator 503 for estimation of the accessing subscriber's broadband spatial signature using, e.g., an FFT based spatial signature estimator or other well-known parametric spatial channel estimation

10   algorithms. The estimated 2-D spatial signature, along with spatial signature of subscribers corresponding to on-going traffic stored in the on-going traffic spatial signature register 506 and on-going traffic information stored in the on-going traffic register 504, are fed to OFDMA/SDMA traffic channel allocation logic 505 to determine a traffic channel assignment for the

15   accessing subscriber, and possibly partial or all of the on-going subscribers. The results are sent to OFDMA MAC 507 that controls the overall traffic.

Control signals from OFDMA MAC 507 and downlink data streams 520 are mixed and modulated by OFDM modulator 510 for downlink transmission. Spatial beamforming can be applied with a set of parallel

narrowband beamformers 509 using spatial information stored in the on-going traffic spatial signature register 506. Specifically, the beamforming coefficients used by beamformers- 509 are calculated based on each subscriber's spatial signature. The output of beamformers 509 are up-

5   converted by the set of up-converters 508, and transmitted through transmission antenna array 511.

In order to find one traffic channel assignment for the requesting subscriber, the traffic channel allocation logic first ranks all traffic channels in the order of the so-called achievable rate for the subscriber. In one

10   embodiment, the achievable rate of the requesting subscriber over a particular traffic channel is limited by the noise power, its channel fading coefficient, and the spatial signatures of all co-channels subscribers in this channel. Other factors include the actual signal processing/communication techniques employed to separate the co-channel subscribers. Once the signal

15   processing/communication techniques (e.g., technology for multi-user beam forming to separate multiple users) are selected, the base-station calculates the achievable data rate for the accessing subscriber and ongoing subscriber(s) over each of the traffic channels as shown in Figure 4. Referring to Figure 4, traffic channels in which on-going traffic are affected

with the addition of accessing subscriber are shaded. In one embodiment,

for the accessing subscriber, its most favorable traffic channels are those

corresponding to the highest rates, e.g., traffic channels 5, 4, 3, ... However,

adding a new subscriber to a traffic channel with on-going subscribers may

5   affect the traffic rates of on-going subscribers. Accordingly, in one

embodiment, only traffic channels in which on-going traffic rates will not be

affected by the addition of the new subscribers are reused. Alternatively,

traffic channels in which on-going traffic is affected by a predetermined

small amount (e.g., a tolerable amount for the application) may be allocated.

10   Other traffic channels are shaded and marked "unusable" (in this case,

traffic channels 1, 5, K-1) to the new subscriber.

       Figure 6 illustrates operations performed by one embodiment of the

traffic channel allocation logic. Referring to Figure 6, inputs to the channel

allocation logic include the 2-D spatial signature of the accessing subscriber,

15   A_new,1 a_new,1, ..., A_new,K a_new,K; the requested data rate, R_new

from storage (not shown); the data rates of on-going traffic in each of the

traffic channels from on-going traffic storage 601; and the 2-D spatial

signatures of on-going subscribers from storage 602.

In one embodiment, the logic starts a loop from traffic channel 1 to traffic channel K and calculates the achievable rate for the accessing subscriber over each of the traffic channels. The results, R_new,1, ..., R_new,K, are saved for further evaluation. In another embodiment, the

5   logic calculates the SINRs in a manner well-known in the art for the requesting subscriber over each of the traffic channels.

In calculating the achievable rate or the SINR value, different spatial processing algorithms, e.g., single-user detection and multi-user detection, may be used. The achievable rate or the SINR value depends on the actual

10   spatial processing algorithm used in practice.

Also calculated are the achievable rates of on-going subscribers at each of the traffic channels with on-going traffic for the case that the requesting subscriber is added to that traffic channel: R_i,k, k=1, ..., K. Similarly, in an alternative embodiment, the logic can calculate the SINR

15   values of on-going subscriber at each of the traffic channels, for that case that the requesting subscriber is added to that traffic channel.

The logic then examines whether these updated achievable rates (or SINRs) are lower than the actual rates (or SINR) requirements of subscribers with on-going traffic (e.g., a minimum data rate requirement that must be

satisfied). Note the actual rate may be higher when extra resources are available of subscribers with on-going traffic. Traffic channels in which the requesting subscriber is added and, therefore, in which the new rates or SINRs drop below the on-going rates or SINR thresholds are labeled

5   "unusable" for the requesting subscriber. The remaining traffic channels are ranked and assigned in a descending order of the achievable rates or SINR values for the requesting subscribers. The thresholds may be set to ensure a specific signal quality at a particular data rate.

The process stops when the total rates for the requesting subscriber

10   exceed a pre-determined value for the requesting subscriber.

Other criteria, e.g., the mean-squared errors of the spatial multiplexing outputs, the packet error rate in the case of packet data, etc., can be used for channel allocations in place of, or in addition to, the achievable rate.

15   Other Quality of Service (QoS) requirements of the new subscriber or other subscribers with on-going traffic, e.g., the packet delay, the throughput, and bit-error-rate, can be used in place of, or together with, the achievable rate or the SINR value in channel allocation.

Whereas many alterations and modifications of the present invention will no doubt become apparent to a person of ordinary skill in the art after having read the foregoing description, it is to be understood that any particular embodiment shown and described by way of illustration is in no

5   way intended to be considered limiting. Therefore, references to details of various embodiments are not intended to limit the scope of the claims which in themselves recite only those features regarded as essential to the invention.